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WELOC: Localizing Equipment in Marinas using Ultrasound

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Abstract—In this paper we propose WELOC, an ultrasound-based localization system for localizing objects in a marina environment. WELOC uses the already installed infrastructure of commercial battery-powered IoT devices, with several years of autonomy, fixed at each slip on the pontoons, used for boat presence monitoring. These devices are equipped with an ultrasound sensor, have known GPS positions and form a wireless, time-synchronized (<15 μ s synchronization error), mesh network around the gateway. Without impacting the main function of the smart parking system for boats, we propose a scheme to schedule when each ultrasound sensor is triggered. We design a mobile device, from an off-the-shelf ultrasound sensor, compatible with those already present in marinas. We synchronize the device with each ultrasound trigger in the marina, and collect the timestamped distance measurements. The location of the mobile device is then computed using trilateration. We test the ranging accuracy of the mobile device in the lab, where we achieve a 3.5 cm mean absolute error, with a maximum range of 10 m. We perform field testing for the ultrasound signal detection inside the marina, which is equipped with 471 presence sensors, one at each of its slips. We show that our mobile device successfully detects the ultrasound signal on the pontoons.

Index Terms—Localization, Low-power wireless, Smart marina, Smart parking, Internet of Things (IoT).

I. INTRODUCTION

Localization is the process of determining the position of a device or a system in its environment. It plays a vital role in robotics, navigation, and remote sensing. In robotics, it enables autonomous vehicles, drones and mobile robots to navigate and perform tasks effectively [1]. It allows them to avoid obstacles and safely reach their destination. In remote sensing and Internet of Things (IoT) applications, localization helps determine the position of sensors, for example to geo-stamp the data being measured [2].

We focus on the specific use case of localization in a marina environment [3]. Marinas are looking for such a system for tracking: boats (to know if they are in the right place and to warn marina operators in case of an unexpected movement which could indicate theft), equipment (to know the location of an important asset or tool in order to improve efficiency) and workers (to ensure that they are safe and working on the right tasks). Additionally, by having real-time information about the location of boats and other watercrafts, marina operators can optimize the use of the pontoons. It can also help boaters navigate the marina and find their desired destination more easily.

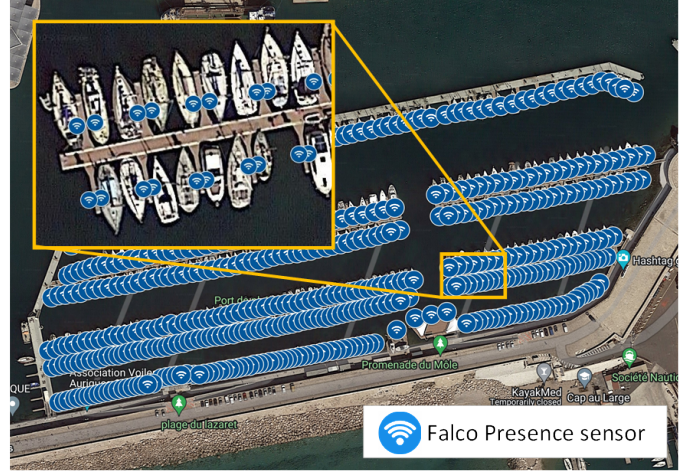


Fig. 1. Falco Presence sensor infrastructure in the Sète marina in the South of France. Each slip inside the marina has a dedicated ultrasound-based sensor for boat detection.

The intuitive approach would be to use the Global Positioning System (GPS). GPS receivers are ubiquitous and we all have them in our cell phones, cars and boats, and it works well outdoors. However, we want to have sub 1 m localization accuracy with years of battery life for our marina use case. A standard GPS receiver cannot provide sub 1 m accuracy and is very power hungry [4]. Another approach could be to use the Received Signal Strength (RSS) measurement to calculate the distance between the two radio devices. When a device receives a radio packet from the transmitter it can obtain the RSS indicator, as most radio chips on the market provide this information “free of charge”. We could then use signal propagation model to estimate the distance between the two devices [5]. By estimating the distance to three or more transmitters we can trilaterate the position of the receiver, if the transmitters’ positions are known. Due to the the nature of the radio signals, multi-path and fading effects can seriously affect the distance estimations. For example, localization systems based on long-range radio technologies offer an accuracy of 100 m - 1 km [6]. A different approach can be the use of localization solutions that have been proposed for the indoor use, but could be considered for the marina use case. They combine fixed devices, pre-deployed at known positions (the “anchors”) through which tags (the “mobile devices”) move. The mobile

devices are located by making measurements relative to the anchors: either distance measurements (this is the case of Ultra Wide Band – UWB [7]), or angle measurements (this is the case of the Angle of Arrival – AoA – standardized by Bluetooth in 2019 [8]). Several comparative studies highlight the trade-off between the localization accuracy obtained, and the density of the anchors [9]. However, the main problem of these solutions is that they require the deployment of dedicated anchors (which form an infrastructure), and the power supply of these anchors, which remain active all the time and thus consume too much to be powered by batteries.

Our focus is on a particular use case of marinas equipped with Falco IoT solutions. Falco is a company that develops and commercializes IoT networks and services for marinas [10]. One of the solutions Falco creates is a service that detects when a slip inside the marina is occupied by a boat. We install Falco Presence sensors at each slip to monitor the presence of a boat, using an ultrasound sensor for distance measurement. Fig. 1 shows the Sète marina in the South of France, which is entirely equipped with the Falco Presence sensors. These battery-powered devices communicate over radio and form a wireless, time-synchronized, mesh network around the central gateway. The distance measurements from all sensors inside the marina are sent to the cloud, where the presence detection algorithm outputs a real-time occupancy of slips on a map. The intuition here is that we already have all the components inside the existing IoT network to enable localization. We have fixed devices with known GPS positions (Falco Presence), all devices are equipped with ultrasound sensors (possibility of distance calculation using Time of Flight – ToF) and Falco IoT network is time-synchronized (allowing precise scheduling of the ultrasound measurements). Therefore, if we add a tracking device inside the marina, which is synchronized with the network and capable of receiving ultrasound signal from the fixed sensors, we can estimate its position relative to them, using trilateration.

In this paper we propose WELOC, a localization system implemented on top of the commercial “Smart Parking for Boats” IoT solution deployed in the marina. By utilizing an already existing infrastructure of ultrasound-based sensors for boat detection, we propose a scheduling scheme for activating these fixed sensors. Without altering their main function for boat detection, we are able to re-use the ultrasound signal for distance calculation between the fixed sensors and a mobile device. We propose the use of an off-the-shelf ultrasound sensor for the mobile device, capable of detecting 42 kHz ultrasound signal present in the marina. We synchronize the mobile device with the presence sensors over radio, timestamp the measured distances and send it over the network to the cloud. We can then estimate the position of the mobile device through trilateration. In order to test our approach, we perform ranging experiments in the laboratory. We show the absolute distance error of 3.5 cm between the anchor and the mobile device, with the maximum range of 10 m between devices. We perform field testing in Sète marina in the South of France. Tests show that we are able to detect ultrasound

signal on pontoons using the proposed mobile device. WELOC is designed as a software/firmware update to an existing IoT solution deployed in the marina. Thus, we avoid the deployment of the new infrastructure of anchor devices to enable the localization. Of course, WELOC can be used as-is in other parking deployments, indoor and outdoor.

The remainder of the paper is organized as follows. Section II presents the requirements for the localization system in marinas. Section III describes the commercial state-of-the-art system for boat presence detection in marinas. Section IV presents WELOC. We discuss the system architecture, mobile device design and show the ultrasound detection experiment in the marina. Section V discusses WELOC’s limitations and future steps to improve the system. Finally, Section VI concludes this paper.

II. REQUIREMENTS

Different applications place different requirements on the localization system; it is important to find the best trade-off between localization technique and technology used [11]. The marina use case described above sets the quantified requirements on accuracy, power consumption, location update rate and absence of infrastructure. The main objective is to address the need to deploy anchors in a localization system and the need to power these anchors. Specifically, we are setting the following requirements to our localization system:

- 1) we need the localization error to be less than 1 m;
- 2) we need the location update at least every 5 minutes;
- 3) we need to stay both low-power and wireless, and not use Wi-Fi and Ethernet networks that might be present in some marinas;
- 4) we need all deployed infrastructure to be battery-powered, and to run for at least 3 years.

III. TODAY’S BOAT PRESENCE DETECTION SOLUTION

In order to design a zero infrastructure dependent localization system, we use the existing infrastructure of wireless sensors inside the marina. We evaluate our approach on the use case of Sète marina in the South of France. This marina is outfitted with a commercial-grade IoT network, designed and supplied by Falco. Falco develops different types of low-power wireless sensors for real-time monitoring of boats, their presence at slips and respective current consumption. Once deployed, the sensors form a wireless mesh network around a central gateway. They communicate over a 2.4 GHz radio, using the IEEE 802.15.4e protocol [12]. Data from the sensors is transferred over the Internet to the cloud application.

One of the IoT solutions that Falco creates is the Smart Parking for boats. This solution automates the process of checking for slip occupancy, which, in most cases today, is done manually. The Sète marina is equipped with Falco Presence devices, installed on each of its 471 slips. These devices are riveted under the pontoons, allowing the real-time detection of boats at each slip, as shown in Fig. 2. Once powered, the device connects to the IoT network and gathers the ultrasound distance measurements.



Fig. 2. Falco Presence sensor riveted on the pontoon to monitor presence of a boat at the specific slip. The sensor is located below the pontoon floor level.

Falco Presence device is equipped with a 2.4 GHz System on Chip (SoC), PCB antenna and an ultrasound sensor, powered with a 3.6 V battery. The sensor outputs a 42 kHz ultrasonic signal for measuring the distance to an obstacle, in this case a boat. In the current version, Falco Presence is configured to trigger its ultrasound sensor every 5 min. Once the ultrasound distance measurement is performed, the device sends the raw data to the gateway without further processing. The data is then sent to the MQTT server, and processed by a boat presence detection algorithm. The output of this algorithm is displayed on a real-time map of the entire marina, accessible through the Falco application.

As we previously mentioned, the communication protocol standard used in Falco IoT networks is IEEE 802.15.4e. One of the most significant features of this standard is the addition of time-slotted channel hopping (TSCH) [13]. TSCH allows devices to coordinate their transmissions in a way that avoids collisions and improves reliability. The sensor are time-synchronized, which reduces the amount of time sensors spend listening for the incoming transmissions. This of course leads to significant reduction of their power consumption. Most of the time sensors are in sleep mode, waking up for a couple of milliseconds to send or receive a packet. Thanks to the efficient design of Falco Presence sensors and its firmware, it can achieve over 3 years of autonomy, powered with a 2.4 Ah capacity battery.

All nodes in an IEEE802.15.4e TSCH network maintain synchronization to one another. Time is cut into timeslots, each typically 10 ms long. Even in the absence of data, a TSCH mote sends an “empty packet” to its neighbor, typically every 30 s. It sends that packet at a very specific time inside a timeslot, called $TsTxOffset$. The receiving mote timestamps when it receives the start of that packet; it can be different from $TsTxOffset$ because the two neighbor motes might have drifted in time. The receiving mote indicates that offset in a field inside the acknowledgement frame; the

transmitting mote uses that information to re-align (“resynchronize”) the edge of the timeslot to that of the receiver. The crystal oscillators used by motes to keep track of time drift at a rate of 10-30 ppm (“parts per million”). Using different drift compensation techniques, even by resynchronizing only every 30 s, commercial TSCH implementation exhibit a maximum de-synchronization of 15 μ s across the entire network [13]. We use this strong networking synchronization in WELOC.

IV. WELOC

The commercial Falco solution for monitoring the slip occupancy in a marina contains all the necessary building blocks for a localization system. First, the presence devices installed under the pontoons have a known GPS position and can serve as anchors relative to which we estimate the position of a mobile device. Second, these devices are equipped with a ultrasound sensor, which is a well known technology for sound-based localization systems. Third, Falco network is time-synchronized, which allows the precise time scheduling of the ultrasound sensors. Therefore, the core intuition behind WELOC is to upgrade the Smart Parking solution from Falco and enable localization.

WELOC uses the available infrastructure of presence sensors in the marina as fixed anchors. Since all presence sensors have a known GPS location, knowing a distance between the mobile device and at least three fixed anchors allows to estimate the position of the mobile device. We can perform the trilateration to determine the location of the mobile device. In Fig. 3 we show the block diagram of the system. WELOC consists of the following: presence sensors (fixed anchors), mobile device (device to be tracked) and a gateway.

The proposed system does not alter the main purpose of the Falco Presence devices, explained in Section III. We trigger the ultrasound measurement of each device with an offset that depends on its unique identifier. Fig. 4 shows the proposed schedule. We want to synchronize the mobile device with each Falco Presence in the marina. In WELOC, the ultrasound triggering functions in a Time Division Multiple Access (TDMA) fashion, where one time slot for ultrasound measurement is 30.2 ms. We take 20 μ s for the ultrasound pulse trigger (writing a HIGH voltage level to the sensor’s trigger pin) and 30 ms for listening for the echo (measuring the ultrasound ToF i.e. distance between the mobile device and a single Falco Presence). We chose the 30.2 ms time window due to the limitations of the ultrasound receiver on the mobile device, which the range limit of 10 m. In one ultrasound ranging cycle, each Falco Presence device in the marina triggers its ultrasound sensor only once. The device measures the distance to an object and performs the boat detection. In the same time, its reflected signal is also picked up by the mobile device. The mobile device triggers the ultrasound reception each time a Falco Presence device triggers an ultrasound measurement. This means that the mobile device triggers the ultrasound reception n times for n number of presence sensors in the marina, where duration of one ultrasound ranging cycle is $n * 30.2$ ms. In its current implementation of

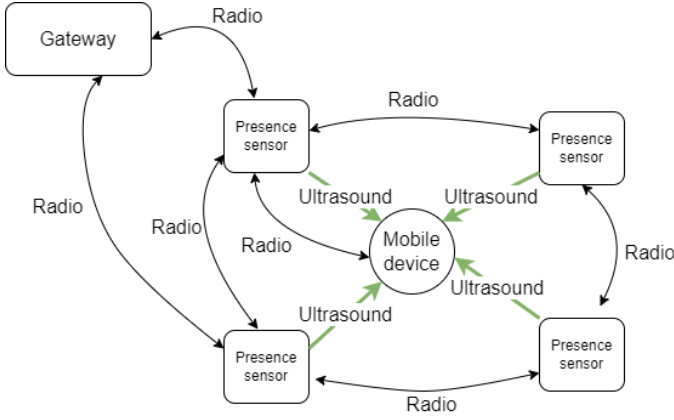


Fig. 3. System block diagram showing the presence sensors and the mobile device, reporting boat detection and timestamped ultrasound ranging measurements to the gateway, respectively.

WELOC, the fastest update rate of localization in Sète marina is 15.1 seconds, which satisfies the application Requirement 2, set in Section II.

When the mobile device records a distance measurement, it also timestamps it. This is done for each recorded measurement in one ultrasound ranging cycle. Let's assume that in one ranging cycle the mobile device records four distance readings. This corresponds to the four Falco Presence device in its vicinity, which have triggered the ultrasound for boat detection. Each distance measurement corresponds to the distance between a single Falco Presence device and the mobile device. These distances are transferred to the gateway after one ranging cycle, and forwarded to the cloud application. We compare the timestamped distance measurement with the ultrasound sensor trigger time to determine from which Falco Presence device the mobile device received the ultrasound signal. We then calculate the position of the mobile device relative to the Falco Presence devices using trilateration. WELOC does not rely on existing mains power infrastructure or Wi-Fi/Ethernet networks. The battery-powered Falco Presence devices, which are used as the anchors in WELOC, offer more than 3 years of battery autonomy. Therefore, WELOC satisfies the application Requirements 3 and 4, set in Section II.

A. Mobile Device

The mobile device is equipped with a 2.4 GHz SoC and an ultrasound sensor. It is capable of time-synchronized communication with the existing wireless IoT devices inside the marina. In order to avoid additional costs for designing a custom ultrasound receiver for the mobile device, we use an off-the-shelf sensor. In our previous work, we show that it is possible to achieve cm-level ranging accuracy by synchronizing off-the-shelf ultrasound sensors, primarily designed for sensor to object distance measurement [14]. We identified the 42 kHz ultrasound sensor, MaxBotix - MB1603, operating at the same frequency as the ultrasound sensors on the Falco Presence. MB1603 has two transducers, one for transmitting and one for receiving the ultrasound signal. If we cover the transmit transducer on the mobile device with tape/foam the sensor

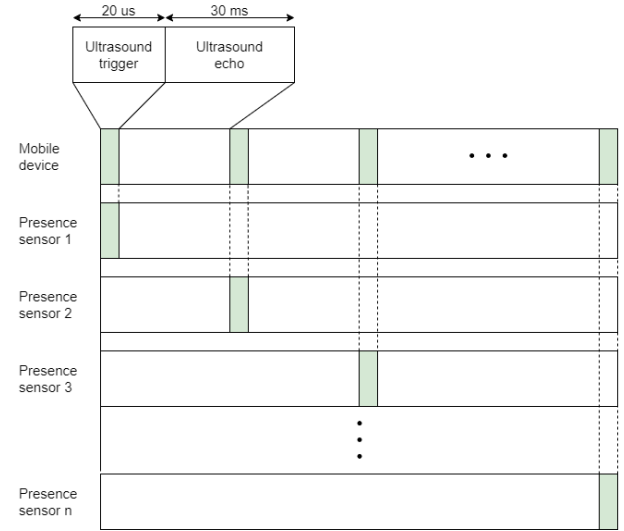


Fig. 4. WELOC ultrasound trigger schedule.

cannot perform distance measurement. Its echo signal will never reach the receiver transducer. However, the functionality of the sensor for measuring the round-trip time is not disabled. If we synchronize the ultrasound transmission on the anchor device (Falco Presence) and on the mobile device (MB1603), we can measure the distance between the two sensors. In order to obtain the actual distance we multiply the output of the sensor by 2, since there is no round-trip time. The MB1603 is designed to measure distances up to 5 m, hence the mobile device maximum ranging of 10 m.

We test the ranging accuracy of the mobile device in the lab. The mobile device's transmitter is covered with tape and has only the receiving transducer active. In this test, the anchor device is a single transducer MaxBotix - MB1010 sensor. It has the same transducer characteristics as the ultrasound sensors deployed in the marina. Both device trigger the ultrasound measurement by having the PIN 4 at high voltage level for more than 20 us. We want to test the accuracy of the ranging in ideal case, assuming perfect network synchronization. We connect both devices with a long cable in order to trigger them with a single switch. When active, the switch pulls the trigger pins on the anchor and the mobile device HIGH at the same time. Fig. 5 shows the test configuration. In order to obtain the results, we use the oscilloscope to measure the PWM output on the mobile device. Here, 1 us duration of the PWM signal corresponds to 1 mm distance to an object. We multiply the output by 2 to obtain the actual distance. For obtaining the ground truth we use laser distance meter.

Fig. 6 shows the absolute ranging error. We obtain the mean absolute distance error of 3.5 cm. As expected from the sound-based ranging systems, we achieve cm-level accuracy up to 10 m of distance between the anchor and the mobile device. In this experiment we have no synchronization error accounted, as we assume perfect synchronization and use a single switch to trigger both sensors. As explained in the Section III, the deployed IoT network in the marina is time-synchronized, with synchronization error of < 15 us. The sub 15 us level

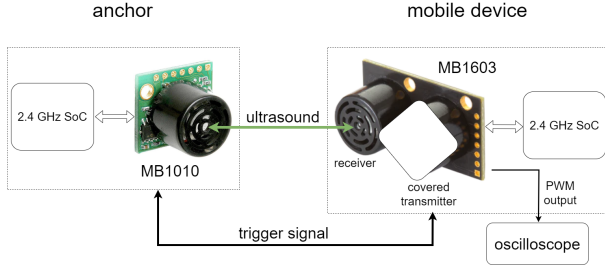


Fig. 5. Block diagram diagram of the ultrasound ranging test in the lab.

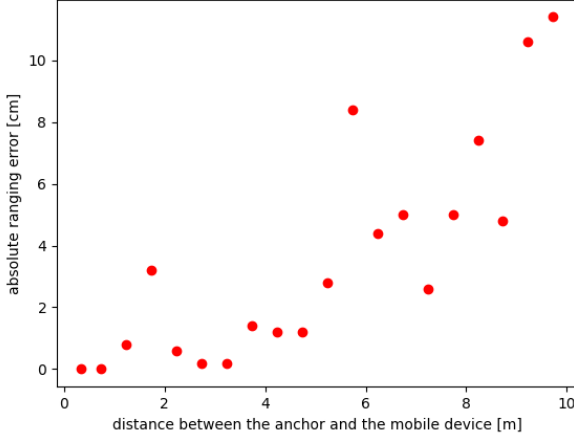


Fig. 6. Absolute ranging error between anchor and mobile device. Measurements are collected from the PWM output pin of the mobile device, while the ground truth is obtained by a laser distance meter.

synchronization corresponds to approximately 5 mm distance error for the sound-based distance measurements. As our localization accuracy requirements are sub 1 m error, the proposed architecture can be used to meet the application Requirement 1, set in Section II.

B. Field Testing

In order to verify that the WELOC system can be implemented in the real-life marina use case, we perform the ultrasound detection with the mobile device in Sète marina. Since the Falco Presence devices are installed on the pontoons, riveted below the floor level, detecting the ultrasound on the pontoons can be challenging. Therefore, we perform this test to verify that we are able to receive the ultrasound from the Falco Presence devices, while walking on the pontoons with the handheld mobile device. The purpose of this experiment is to check the feasibility of WELOC with a hands-on experiment. Therefore, we do not timestamp the distance measurements obtained by the mobile device, but rather check for the presence of the ultrasound on the pontoons.

We configure the Falco Presence devices to trigger ultrasound ranging every 5 s. This allows us to perform ultrasound detection with faster rate, compared to the default Falco Presence operation (ranging every 5 min). We use the oscilloscope to capture the value of the analog output pin of the mobile device. When there is no signal detected we observe 3 V output. When an ultrasound signal is detected the



Fig. 7. Diagram shows the ultrasound signal detection in the Sète marina in the South of France. We depict the positions and orientations of the mobile device on the pontoon during the experiment. The mobile device successfully detects the ultrasound signal emitted by the Falco Presence devices, as shown by the oscilloscope screen captures of the analog output signal. When the signal drops below 3 V the ultrasound signal is received.

analog signal drops below that value, which means that we captured an ultrasound signal coming from a Falco Presence. We perform the experiment at the pontoon E, inside the Sète marina.

We run the experiment with 28 Falco Presence devices reconfigured to trigger ultrasound every 5 s. We hold the mobile device in hand, 1.5 m above the pontoon. For each position of the mobile device we monitor the analog output pin. We point the mobile device to different directions, as shown in Fig. 7. We can see that, for each of the positions depicted, the mobile device can detect the ultrasound signal on the pontoon. This experiment shows that the implementation of WELOC is feasible in a real-life marina use case.

V. DISCUSSIONS AND FUTURE WORK

Although WELOC meets all the application requirements, described in Section II, there are limitations of the current system that could be improved in the future. In this section we highlight the major limitations and possible optimization approaches for future work.

There are many sound-based localization systems proposed in the literature, offering cm-level localization accuracy [11]. Apart from the academic research, state-of-the-art commercial solutions offer cm-level asset tracking accuracy, combining technologies like ultrasound and radio [15]. In order to obtain this level of accuracy sound-based systems require Line of Sight (LoS). WELOC relies on the ultrasound multi-path signals. Falco Presence device has a direct LoS with the boat it is monitoring, but the mobile device located on the pontoon is, in most cases, receiving the reflected ultrasound signal. This increases the error in the mobile device's position estimation. However, in this paper we are not aiming for the cm-level accuracy of the sound-based systems, as the accuracy requirement is a localization error of less than 1 m. The dense deployment of Falco Presence devices inside the

marina minimizes the localization error caused by the reflected ultrasound signal. Moreover, when a boat is located at the slip, the LoS distance between a Falco Presence device and a boat is less than 20 cm. In the case of an absence of a boat, the mobile device can have direct LoS with the Falco Presence device, allowing a cm-level ranging accuracy.

In most sound-based localization systems available in literature, the anchors are installed above the mobile device, in order to minimize the number of anchors needed and allow a better ultrasound signal coverage. As we show in Section III, Falco Presence devices are riveted under the pontoons, at each slip inside the marina. Using these devices as anchors in a localization system is not ideal, due to their location under the floor level. However, we could improve the coverage of signal by equipping other IoT devices inside the network with ultrasound sensor. In the Falco IoT network, apart from the sensing devices, we install wireless repeaters above the pontoons in the marina, each located approximately 10 m from each other. These devices serve as relays inside the network, providing good wireless communication links between the IoT devices and the gateway. We could improve ultrasound signal coverage in WELOC by equipping these repeaters with one or more ultrasound sensors. This would also improve the accuracy of the system, as the repeaters are located on the poles above the pontoons, with the direct LoS with the mobile device.

In the current WELOC implementation, a mobile device needs to activate its receiver each time a Falco Presence device triggers its ultrasound sensor. In the real-life use case shown in Section III, there are 471 Falco Presence devices, and one ultrasound ranging cycle lasts for 15.1 s. For most of the time the mobile device is performing ranging without receiving ultrasound signal, because it is far away from most of the Falco Presence devices in the marina. The mobile device is located on a pontoon with only a few fixed devices in its proximity. Therefore, optimizations could be made to improve the localization update rate and battery life of a mobile device. In WELOC, we could use RSSI to determine at which pontoon or part of it the mobile device is located. The mobile device has a wireless radio, time-synchronized with the IoT network, and it is capable of measuring the RSSI of its neighbor devices (Falco Presence). This way we could first have a rough location estimation of the mobile device, for example a pontoon at which it is located, and then schedule the ultrasound transmissions of its neighboring Falco Presence devices.

VI. CONCLUSION

This paper introduces WELOC, an ultrasound-based localization system for localizing objects in a marina environment. By leveraging the existing infrastructure of commercial IoT devices equipped with ultrasound sensors, we were able to design a system that can accurately and efficiently localize objects on the pontoons. Our system features a scheduling scheme that allows us to determine which sensor triggered the ultrasound at any given time, without altering the main function of the Smart Parking system for boats. To evaluate

the performance of our system, we designed and tested a mobile device using an off-the-shelf ultrasound sensor that is synchronized with each ultrasound trigger in the marina. Our lab tests showed that the mobile device achieved a mean absolute error of 3.5 cm in ranging accuracy, with a maximum range of 10 m. Field testing in the marina, equipped with 471 presence sensors at each slip, demonstrated that our mobile device successfully detected the ultrasound signal on the pontoons. WELOC presents a promising solution for localizing objects in a marina environment using existing infrastructure and off-the-shelf components, thus avoiding complex hardware design and additional installation costs. Integrating our system into existing Smart Parking systems for boats is simple and straightforward since it only requires a firmware or software update. Future work could involve further optimizing the system for improving the update rate and battery life of the mobile device, as well as exploring additional applications beyond marinas.

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